Development of Crispness in Cookies During Baking in an Industrial Oven

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ABSTRACT

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A phenomenological investigation was made of some physical processes that develop during an industrial baking operation of hard sweet biscuits (cookies). Samples were collected in different locations from a continuous belt oven corresponding to different baking times. The effects of time on volume, structure, weight, and color of cookies were monitored. Mechanical behavior was also investigated by submitting the cookies to a three-point bending test. The modulus of elasticity correlated well with the sensory perception of cookie crispness. By comparing the kinetics of elasticity of cookies during baking with that of the observed physical phenomena taking place, it was possible to relate the development of crispness to physical processes occurring during baking.

From the physical point of view, the baking process of cookies consists of a thermal treatment that promotes dough structuring and dehydration and the development of browning reactions. The final result of this operation is a product characterized by a cellular structure and peculiar mechanical properties. Due to these characteristics, hard sweet biscuits (cookies) are perceived as crisp materials when submitted to sensory analysis. As a matter of fact, crispness is the most important sensory attribute of this class of baked products. It determines to a great extent the consumer acceptability and represents the critical factor that limits their shelf life.

Crispness originates from a combination of physical, mechanical, acoustical, vibratory, and tactile phenomena. However, many studies reported in scientific literature demonstrate that crispness can be correlated with selected physical qualities such as rheological properties (Bruns and Bourne 1975, Jowitt 1979, Zabik et al 1979, Gormley 1987, Bramasco and Setzer 1990, Heist and Cremer 1990, Sauvageot and Blond 1991, Gaines et al 1992a,b) or acoustic properties (Vickers and Bourne 1976, Christensen and Vickers 1981, Seymour and Hamann 1984, Vickers 1988, Lee et al 1990).

The exact molecular mechanism responsible for the loss of crispness has not yet been elucidated. The only certainty is that crispness of hard dough cookies is very sensitive to moisture content. It has been theorized (Katz and Labuza 1981, Tubert and Iglesias 1986, Sauvageot and Blond 1991) that crispness is related to the amount of water bonded to the carbohydrate matrix, which, in turn, affects the relative mobility of the amorphous and crystalline regions. More recently, the transition from the crisp to the noncrisp state of cereal-based products caused by moisture was explained in terms of variation in the glass transition temperature (T_g) (Nelson and Labuza 1993, Slade and Levine 1994, Le Meste et al 1994). Slade and Levine (1990), demonstrated that the T_g of these food materials depends exponentially on moisture content. Basically, the texture profile of cereal-based foods depends on the relative mobility of functional constituents, and the T_g provides a measure of this relative mobility. Below the T_g the relative mobility among functional constituents is small; above the T_g it is high. Foodstuffs with a T_g quite above the consumption temperature are crisp; the opposite occurs for food materials with a T_g close to or below that of the consumption temperature.

Another way to look at the transition from the crisp to noncrisp state of cereal-based food materials was to consider the failure behavior. Parker and Smith (1993) and Attenburrow and Davies (1993) associated the changes in the state of crispness to the transition from brittle to ductile behavior, which is observed with varying the moisture content, the temperature, and the stress state of these foodstuffs.

Although a large effort has been made to describe the relationship between cookie crispness and composition and structure, very little information is available about the development of crispness as a result of the physical processes that take place during baking. This notwithstanding, the paramount importance of this information is in respect to optimization procedures and packaging design. From the phenomenological point of view, the cookies undergo physical changes during baking in an industrial oven, and there is a relationship between these physical changes and the sensory perception of crispness.

MATERIALS AND METHODS

Commercial hard-dough cookies made by sheeted and moldered were dough used (Bringiotti 1992). The cookies were rectangular shaped with dimension averages measured by caliper for length, width, and thickness at 60.45, 48.3, and 5.55 mm, respectively. Samples were also taken during baking in a continuous tunnel band oven, indirectly fired, 90-m long, and operating at a band speed of 0.31 m/sec. The temperature in the oven was not con-

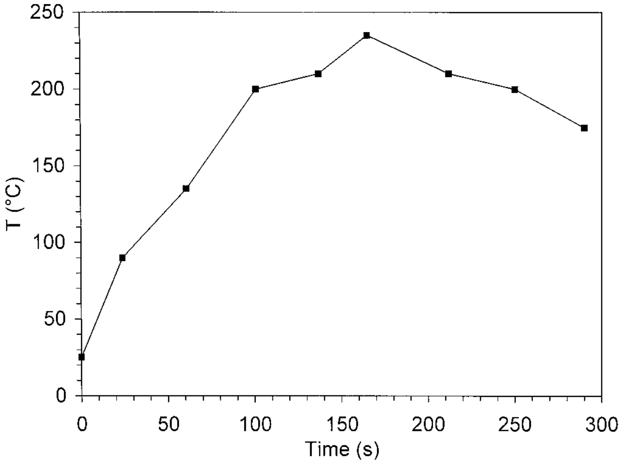

Fig. 1. Temperature profile measured in the industrial oven used to produce cookies.

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stant, but it varied according to the profile represented in Figure 1. The overall baking time was 290 sec. The average moisture content of the finished cookie was 0.013 g of H_2O/g of dry matter, which is the same as that of the cookies taken from integer-wrapped packages. Samples were collected along the oven through doors located near the temperature probes.

Samples utilized in sensory analysis and in some instrumental tests were conditioned at different moisture contents from 0.02 to 0.16 g of H_2O/g of dry matter. For this purpose, a climatic chamber (Heraus HC 0020, Votsch GmbH, Badingen, Germany) was set at 40ºC and 95% rh. Cookies were stored in the chamber for 5, 15, 30, and 90 min to obtain samples with different moisture contents. The samples used to determine the sorption isotherm and in some instrumental tests were obtained by equilibration at 25ºC over saturated salt solutions (H_2SO_4, LiCl, CH_3COOK, $MgCl_2$, K_2CO_3, NaBr, $NaNO_2$, NaCl, and KCl) in desiccators until a constant weight was reached. To prevent the formation of mold, the desiccator walls were sprayed with an antimold solution (Nizorai Ketoconazole, Janssen, Latina, Italy). The actual moisture content of the samples prepared according to both procedures was evaluated after oven drying for 12 hr at 105ºC.

Inspection of cookies with different water contents was performed with an electron light microscope (Stereo Scan 250 XW, Cambridge Co., England), after freeze drying (Lyoflex 04, Edwards High Vacuum, Crawley, West Sussex, England) and metallization of the samples.

Force-deformation tests were performed by using a UTM (model 4301, Instron Ltd., High Wycombe, U.K.) interfaced with a PC for automatic data collection (software Instron Series IX, Automated Materials Testing System). The apparatus was equipped with a three-point bending fixture with a 36-mm span bridge, 100 N load cell. The tests were performed using a crosshead speed of 50 mm/min. The tangent modulus of elasticity was calculated from the steepest initial straight-line portion of the load-deflection curve using the relationship (ASTM 1971):

$$E = L^3 s / 4bd^3)$$

where E is the modulus of elasticity in bending (Pa); L is the support span (m); b and d are the width and the depth of the cookie

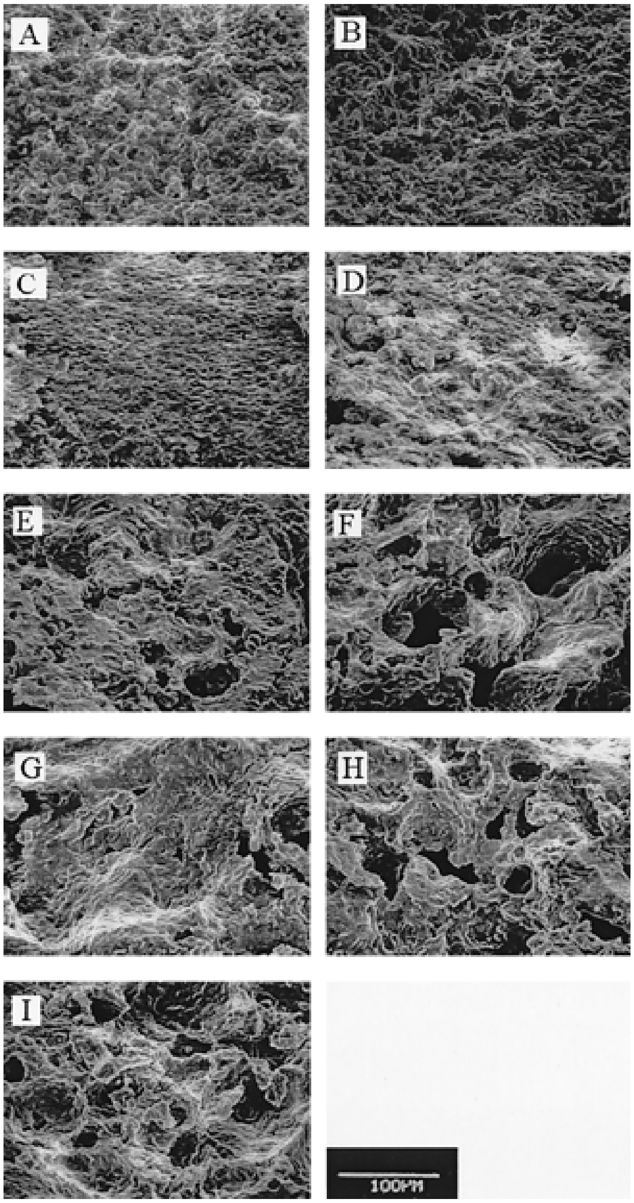

Fig. 2. Scanning electron micrographs (200×) of the fracture surface of samples collected along the oven belt at various distances from the entrance oven corresponding to various residence times (sec): **A** = 0; **B** = 24; **C** = 61; **D** = 101; **E** = 137; **F** = 165; **G** = 212; **H** = 250; **I** = 290.

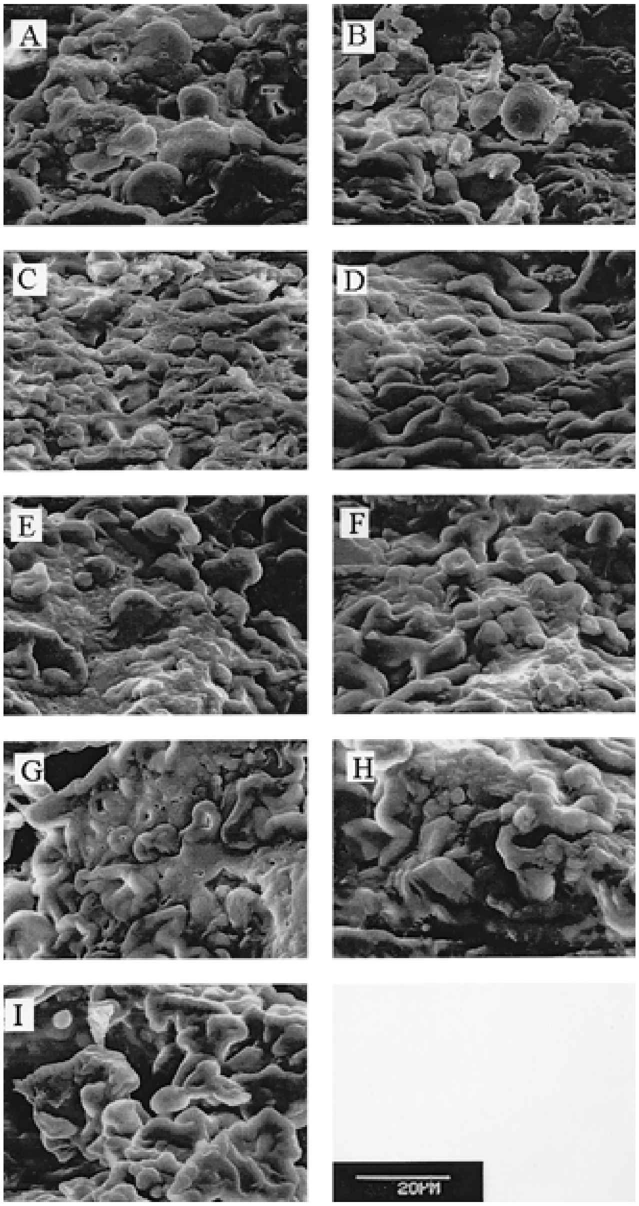

Fig. 3. Scanning electron micrographs (1,000×) of the fracture surface of samples collected along the oven belt at various distances from the entrance oven corresponding to various residence times (sec): **A** = 0; **B** = 24; **C** = 61; **D** = 101; **E** = 137; **F** = 165; **G** = 212; **H** = 250; **I** = 290.

(m), respectively; and *s* is the slope of the tangent to the initial straight-line portion of the load-deflection curve (N/m) of deflection. Energy at failure (J) was also measured as the area subtended to the curve up to failure. Results reported are the arithmetic mean of 10 independent tests.

Cookie bulk density was evaluated by determining the sample weight and the sample volume. The volume was determined according to the rapeseed displacement method.

Color measurements were performed with a colorimeter (Chroma Meter II, Minolta) and were expressed in a *L, a, b* coordinate system.

The sensory analysis was performed by a 15 member panel trained on various products exhibiting different levels of crispness. They were asked to evaluate crispness and the overall hedonic acceptability. They were instructed to evaluate perceived crispness during the first few bites when samples were put between their front teeth. A score test was performed, using a structured rating scale of 1–9. Cookies were served at room temperature in a laboratory open area. Cups of water were provided. The experimental design was based on three replicates, every assessor participated at three work sessions. The data were submitted to the analysis of variance (ANOVA) statistical analysis.

RESULTS AND DISCUSSION

Figure 2 shows the electron micrographs of the fracture surface of samples collected along the oven belt at various distances from the entrance of the oven. Proteins and starch globules can be easily recognized in the micrographs corresponding to samples with <60 sec residence time in the oven. For residence times >60 sec, the single functional constituents of dough progressively lose identity, giving rise to a homogeneous three-dimensional structure. Figure 3 shows the same fracture surfaces but at lower

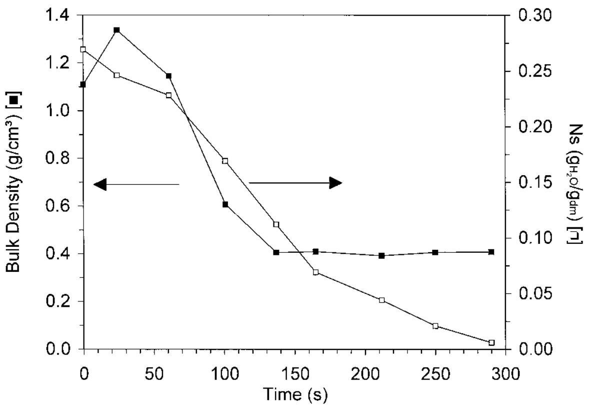

Fig. 4. Bulk density (■) and moisture content (□) of the cookies vs. residence time (sec).

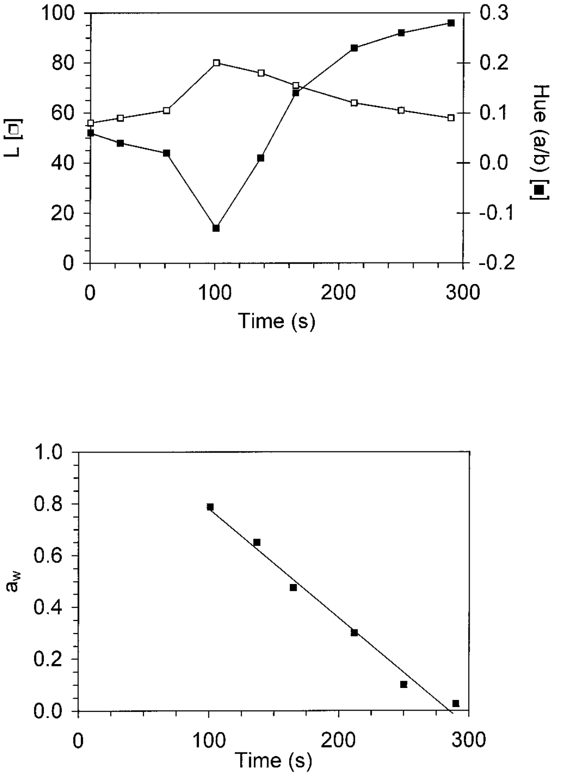

Fig. 5. Luminosity (□), hue (■), and water activity (a_w) of cookies vs. residence time (sec).

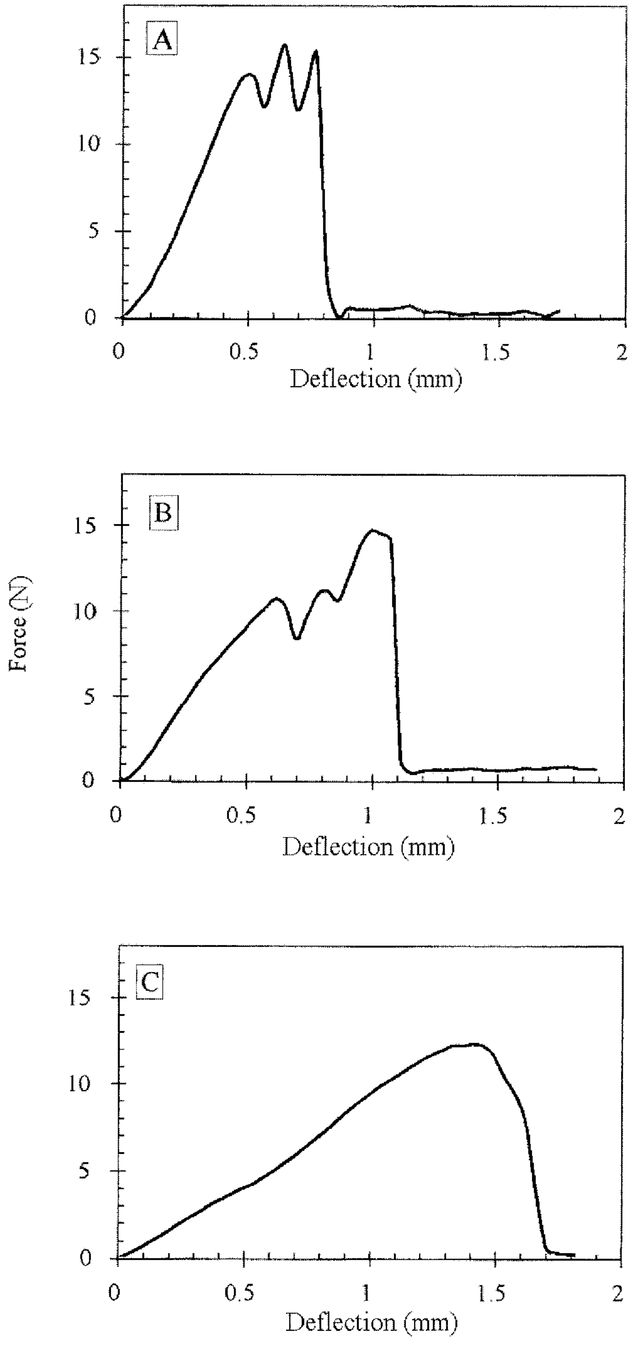

Fig. 6. Force deformation curves of cookies with different moisture contents (g of H_2O/g of dry matter): **A** = 0.034; **B** = 0.09; **C** = 0.114.

enlargements. Development of voids during the leavening process is quite evident. Holes of notable dimensions are observed only in cookies that were in the oven for ≥100 sec. Once cavities are formed in the dough, their average number and their dimensions do not change significantly with increasing the residence time. This suggests that the spongy structure that characterizes hard cookies develops completely during the first part of the baking operation. The fracture surfaces shown in Figure 3 show that the failure behavior of the cookie is ductile when the sample resides in the oven <60 sec and becomes fragile when the residence time is >100 sec. Moreover, no difference in the fracture surface can be noticed among samples with residence times >100 sec.

Figure 4 shows the apparent density of the cookies as a function of the residence time. Immediately after the cookies enter the oven, their apparent density increases, probably as a consequence of fat melting. Then the density decreases and becomes nearly constant after 150 sec of baking. Figure 4 also shows the variation of the absolute moisture content of the cookie during baking. Three different stages characterize the drying process and the drying rate in grams of $H_2O/(g_{dm})(sec)$ remains almost constant during each of them: 1) the drying rate for the first 60 sec of baking is ≈6.6 (10^{-4}); 2) it increases to 1.65 (10^{-3}); and then 3) decreases to 4 (10^{-4}).

It is well known that drying kinetics depend on temperature. Therefore, if the temperature of the cookie varies as it travels within the oven, the observed variation of the drying rate is reasonable. However, the temperature profile along the path of the cookies does not completely justify the drying behavior observed during baking. In particular, the change in drying rate does not correspond to analogous variations in the heating rate. It is probable that, in addition to temperature, the void formation inside the dough plays a certain role. The period during which the drying rate is higher corresponds to the period during which voids form within the cookie. Therefore, one can conclude that the vapor permeation rate increases due to the void formation, resulting in the enhancement of the overall drying rate.

Figure 5 shows the development of the color of the surface of the cookie during the baking process, as well as the water activity values corresponding to the absolute moisture content of the cookies at different residence times. Note that the brown color starts developing only after 100 sec of baking. At that time, the water activity corresponding to the absolute moisture content of the cookies is ≈0.7 a_w. This value is within the range of water activity values for which the nonenzymic browning reactions proceed at the maximum rate (Karel 1984).

To describe the development of the cookie crispness during the baking, it was necessary to select an appropriate parameter to correlate with the sensory perception of crispness. Since crispness is mainly evaluated by biting the cookies with the front teeth, the attention is focused on mechanical properties derived from flexure tests.

First, samples collected at the oven exit and conditioned at different moisture contents in a climatic chamber were examined to elucidate the relationship between moisture content of the cookies and their mechanical behavior when submitted to flexure tests. Figure 6 shows the force-deflection curves with variations in moisture content of the cookies. The curve for the sample with the lowest moisture content presents a sharp rise of the force with varying deflection and a large number of peaks that originate in the progressive breakdown of the cellular structure of cookies. With increasing the moisture content, the force-deflection curve modifies: the initial slope decreases and the number of peaks diminishes.

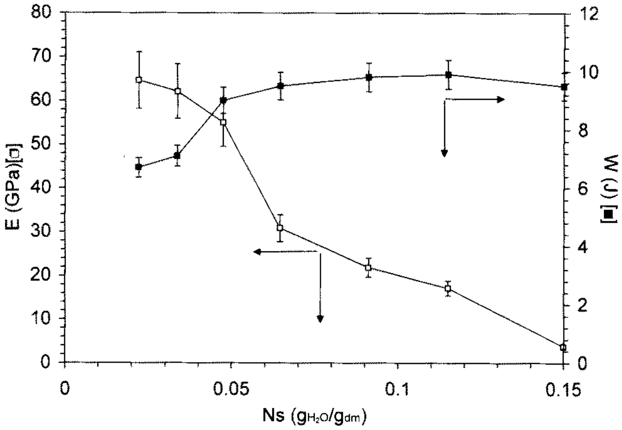

Fig. 7. Modulus of elasticity (□) and energy at failure (■) of cookies vs. moisture content.

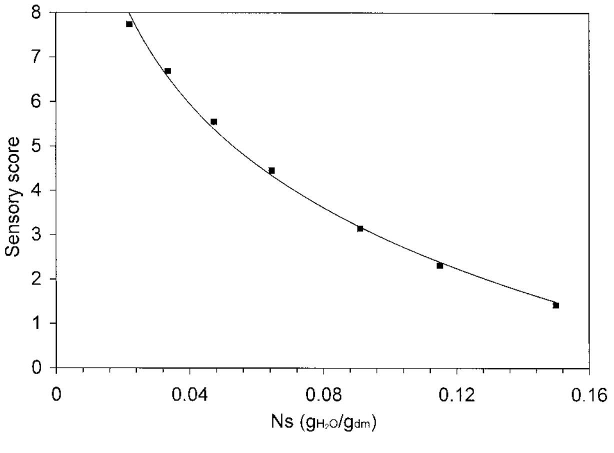

Fig. 8. Sensory score of cookies with different moisture contents (g of H_2O/g of dry matter).

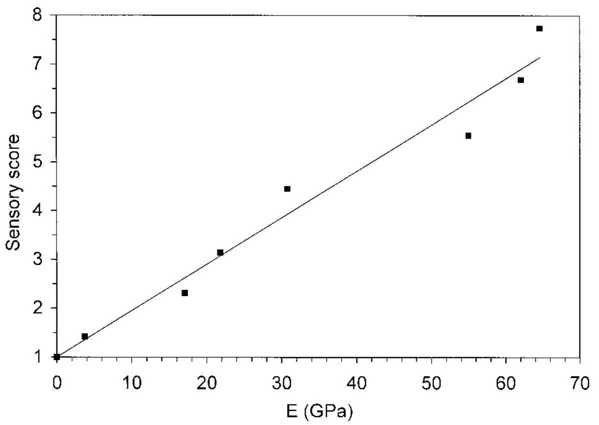

Fig. 9. Sensory score of cookies with different moisture contents vs. the modulus of elasticity.

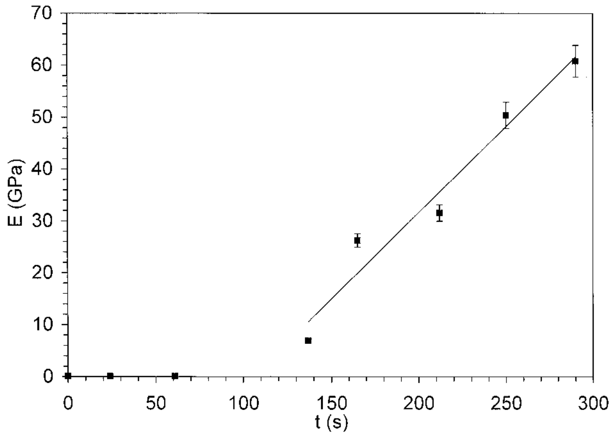

Fig. 10. Modulus of elasticity of cookies vs. residence time.

Many parameters can be derived from the force-deflection curves. In Figure 7, the energy at failure and the modulus of elasticity in bending are plotted against moisture content. Energy at failure provides a measure of the work required to break the cookie. Modulus of elasticity in bending is a measure of the strength of the cookie. This parameter is the only one that decreases uniformly with increasing moisture content. The energy at failure increases at first and then becomes nearly constant as the samples become very moist.

Samples were submitted to sensory analysis. In Figure 8, the sensory score of crispness is plotted against moisture content. As expected, the sensory score of crispness decreases continuously as the moisture content of cookies increases. For our purposes, it is interesting to note that sensory crispness varies when varying the moisture content of the cookie in a way similar to the modulus of elasticity, but quite differently from the energy at failure. The explanation of this diversity is not the purpose of this work. Moreover, Figure 9 shows that the sensory score of the panelists for cookie crispness at various moisture contents is linearly correlated with the modulus of elasticity evaluated by submitting the cookies to bending tests. Consequently, the modulus of elasticity in bending was used to estimate the cookie crispness at different stages of baking.

Cookies taken out of the oven at different distances from the entrance were submitted to a bending test to gain indirect information about the development of crispness during baking. Figure 10 plots the modulus of elasticity against the residence time in the oven. The modulus of elasticity with residence times <100 sec is not detectable. The samples were so weak that they could not sustain their own weight. It was impossible to perform bending tests until the absolute moisture content of the cookies was lowered to 0.15 g of H_2O/g of dry matter. Beyond this limit, the modulus of elasticity increases with a constant rate with increased baking time.

Development of crispness is related to the formation of the spongy-like structure of the cookies and to moisture content, which is fundamentally important in determining the consumer acceptability of cookies.

Figure 11 shows the variation of the modulus of elasticity of the cookie as a function of the moisture content in two different cases. One curve describes data relative to samples collected at different baking times and is representative of the way crispness develops during baking. The other curve is relative to data obtained by analyzing cookies that were baked and then exposed to moist air and is representative of the way crispness is lost when cookies are exposed to air without appropriate protection or during their shelf life if not properly packaged. The horizontal line in Figure 11 is the acceptability limit determined in the sensory analysis. Cookie acceptability is very sensitive to moisture content, and appropriate moisture levels are reached only at the very end of the baking process. Note, also, that the two curves do not coincide. When the cookie takes up water during storage or during consumption, the acceptability limits are exceeded; the moisture content is higher than the value necessary during baking.

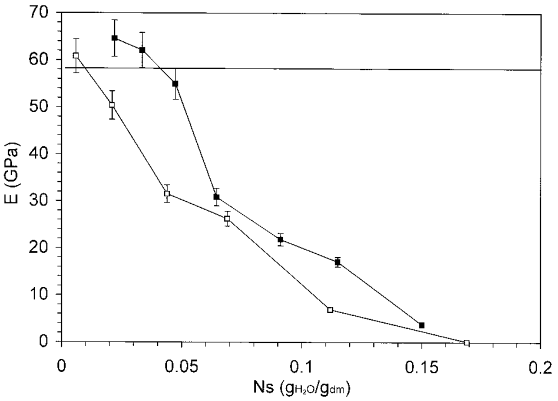

Fig. 11. Modulus of elasticity of cookies vs. moisture content, evaluated during baking operation (□) and evaluated after conditioning in an environmental chamber (■).

CONCLUSIONS

The experimental observations of this study provide some interesting conclusions, particularly the reciprocal influence of the main processes that take place during baking and the role they play in the development on time of crispness.

The formation of the spongy-like structure that characterizes hard sweet cookies is completed during the first 150 sec of baking. The formation of voids within the dough influences to a great extent the drying kinetics of the cookies. Most of the moisture initially present in the dough is removed during the stage at which voids form. The kinetics of decreasing moisture content are important for the browning phenomena. Browning reactions start only when the average moisture content of the cookies reaches $\geq 0.7\ a_w$.

Although the analysis of the baking process was limited to phenomenological aspects, this study gives useful practical information on the development of industrial baking processes. Moreover, it represents a starting point for further investigations concerning the molecular mechanisms responsible for hard cookie crispness, which will be reported later.

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